

# How to Interpret a Tau Excess at LEP2 within the MSSM

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## Abstract

Neutralino and tau slepton pair production can naturally produce an excess of tau lepton pairs at the current LEP collider energies. We describe the constraints this has on the values of the mass parameters in the softly broken Supersymmetric Lagrangian, and consider the consequences for superpartner production at LEP and at the Fermilab Tevatron collider. The pair production of the LSP and a heavier neutralino, followed by a 2-body decay to a tau slepton and tau lepton, is consistent with the present LEP data, predicts a chargino mass below 125 GeV, and provides an interesting Cold Dark Matter component, with  $\Omega h^2 \sim .1 - .2$ .

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## I. INTRODUCTION

Recent measurements at LEP suggest an excess of events containing pairs of tau leptons, though the observation is only of marginal statistical significance [1]: around  $3\sigma$  ignoring systematic errors. It is interesting to study such a possibility, even if only to prepare oneself for the future when the first definitive hint of physics beyond the Standard Model emerges. An excess of tau lepton pairs could arise from the direct production of a pair of tau sleptons, which subsequently decay to tau leptons and gravitino or neutralino LSP's. The tau sleptons may also be produced indirectly in the decays of charginos or neutralinos. Using the available data, a kinematic and dynamical analysis is performed to exclude some mechanisms and constrain others. Based on this, one can more easily establish the existence of a small signal if it is there. We map out the softly broken SUSY Lagrangian, show how the mass and wave function of the LSP can be deduced from kinematic distributions and event rates, and study the implications for the Fermilab Tevatron.

## II. THE DATA AND ITS SUSY INTERPRETATION

An overall excess of tau leptons is observed in all four LEP experiments in a sample of  $220 \text{ pb}^{-1}$  of data per experiment accumulated between  $\sqrt{s} = 2E_{beam} = 192$  and  $202 \text{ GeV}$ . There appears to be a threshold above  $\sqrt{s} = 183 \text{ GeV}$ , possibly above  $\sqrt{s} = 189 \text{ GeV}$ , with a steady excess distributed over energy. The excess sets the size of the production cross section times branching ratio times detection efficiency at about  $.03 \text{ pb}$ . The kinematics are indicative of a large mass splitting  $\Delta M$  between a heavier superpartner and the LSP. No other excesses are reported by all four experiments. Our objective is to take this observation seriously and consider its SUSY implications.

The experimental analysis assumes a specific SUSY signal with a range of  $\Delta M$  values, and cuts on the observables are optimized for this signal. There is no direct measurement of  $\Delta M$ . Instead, quantities such as the visible energy  $E_{vis}$  are measured which are correlated with  $\Delta M$ . In the remainder, we will focus on the fraction of visible energy  $x_{vis} \equiv E_{vis}/\sqrt{s}$  as the main characteristic of the signal. The  $\Delta M$  range depends on the hypothesized SUSY signal, and thus is different for slepton pair production or neutralino/chargino production. For slepton pair production, the L3 experiment analyzes the low, medium, and high  $\Delta M$  ranges defined as  $5-20$ ,  $20-40$ , and  $40^+ \text{ GeV}$  [2]. For tau slepton production, the maximum value in each range is degraded somewhat, since tau decays have an intrinsic missing energy. For neutralino or chargino pair production, the upper end of each range is roughly double those for slepton pair production [3]. This can be understood roughly as the difference between the kinematics of 2- and 3-body decays.

The optimized cuts used by L3 for the large  $\Delta M$  signal of the tau slepton analysis can be

summarized as two reconstructed clusters of particles satisfying the following requirements [2]:

$$\begin{aligned}
.1 \leq x_{vis} \leq .4 \quad .05 \leq \frac{p_T}{\sqrt{s}} \leq .3 \\
E^\ell/E_{beam} < \frac{1}{3} \quad \sin \theta > 0.55 \quad \Delta\phi_{\tau_1\tau_2} < 2.77.
\end{aligned}
\tag{2.1}$$

The experimental quantities used above are the summed  $p_T$  of the two clusters, the electron or muon energy  $E^\ell$ , the polar angle  $\theta$  of the missing energy vector  $\not{p}^\mu = p_{e+}^\mu + p_{e-}^\mu - p_1^\mu - p_2^\mu$  where 1 and 2 denote the two final state clusters, and the azimuthal angle between the two clusters  $\Delta\phi_{\tau_1\tau_2}$ . When a quantitative measure of the efficiency is needed, the signature  $e$  or  $\mu$ +low-multiplicity hadronic cluster is used, since it represents a large branching fraction with little QCD background. These cuts have an efficiency of approximately 0.3 on an hypothesized signal of tau slepton production.

Our starting hypothesis for a phenomenological analysis is that the tau excess results from the production of tau slepton, neutralino, or chargino pairs or some combination of these. For reference, various sparticle production cross sections are shown as a function of collider energy in Figure 1. The sum of the  $\widetilde{N}_1\widetilde{N}_2$  and  $\widetilde{N}_1\widetilde{N}_3$  processes is shown for the cases of  $M_{\widetilde{N}_1} + M_{\widetilde{N}_3} = 180, 185$  and 190 GeV (short-dashed lines), the  $\widetilde{\tau}_R\widetilde{\tau}_R^*$  process for  $M_{\widetilde{\tau}_R} = 80, 85$ , and 90 GeV (solid lines), and the  $\widetilde{C}_1^+\widetilde{C}_1^-$  process for  $M_{\widetilde{C}_1} = 90, 95$ , and 97 GeV (long-dashed lines). The cross sections were calculated using PYTHIA [4], with  $M_1 = \frac{1}{2}\mu > 0$ ,  $\tan\beta = 5$ ,  $M_2 = M_{\widetilde{e}_L} = M_{\widetilde{e}_R} = 300$  GeV for neutralino pair production, and  $\mu = -1$  TeV,  $\tan\beta = 5$ ,  $M_1 = 40$  GeV, and  $M_{\widetilde{\nu}_e} = 100$  GeV for chargino pair production.

The data points, denoted by the circles with error bars [5], are from a preliminary analysis by the LEP SUSY Working Group assuming tau slepton pair production. The data appears to be compatible with direct tau slepton production and  $M_{\widetilde{\tau}} \simeq 80$  GeV or with  $\widetilde{N}_1\widetilde{N}_j$  production with  $M_{\widetilde{N}_1} + M_{\widetilde{N}_3} = 185$  GeV and a heavier tau slepton. Because of its quick rise with energy, the chargino cross section does not agree well with the data. In the next few sections, we fill in the details surrounding these statements. Since neutralino pair production is an indirect source of tau sleptons, we describe first the simpler case of direct tau pair production.

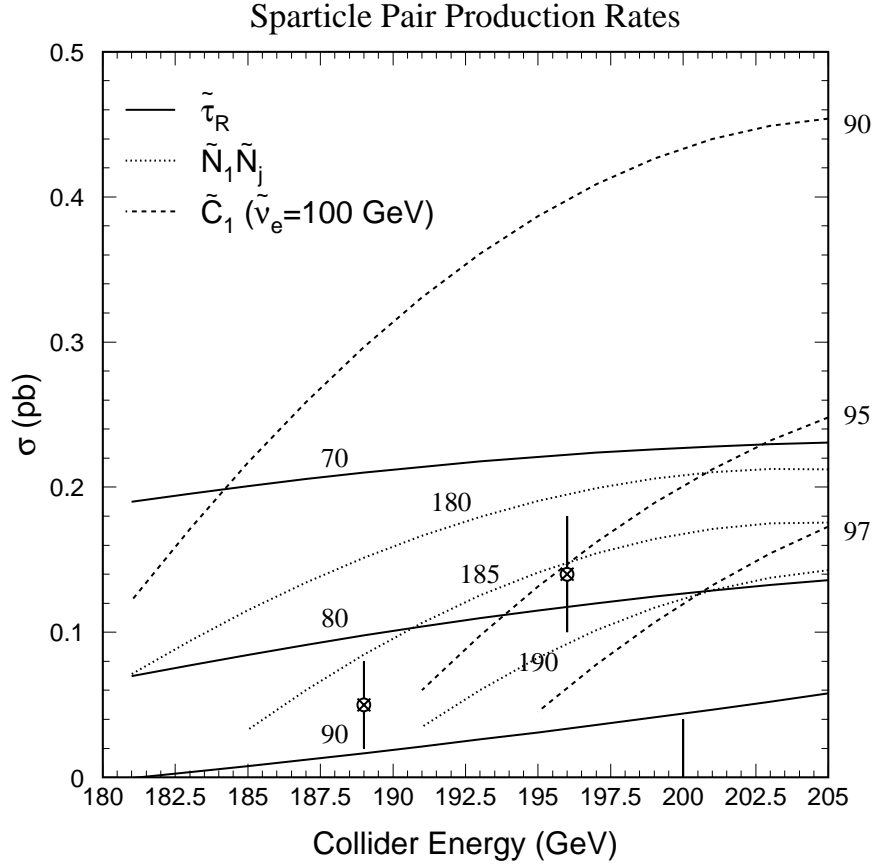


FIG. 1. Sparticle pair production rates from  $e^+e^-$  annihilation as a function of center-of-mass energy. The data points are preliminary results of the LEP SUSY Working Group.

### A. Tau slepton pair production

The production and decay chain  $e^+e^- \rightarrow \tilde{\tau}_1(\rightarrow \tau^-\tilde{\psi})\tilde{\tau}_1^*(\rightarrow \tau^+\tilde{\psi})$ , where  $\tilde{\tau}_1$  is the lightest tau slepton and  $\tilde{\psi}$  may be a light gravitino or the lightest neutralino, can produce an excess of tau leptons with missing energy. For simplicity of the discussion, it is assumed that the  $\tilde{\tau}_1$  is a pure interaction eigenstate, either  $\tilde{\tau}_L$  or  $\tilde{\tau}_R$ . Tau slepton pairs are produced through  $\gamma^*$  and  $Z^*$  decays. The  $Z^*$  contribution depends on the tau eigenstate, but this effect is small. The  $\tilde{\tau}_L$  cross section is slightly larger than the  $\tilde{\tau}_R$  one, and in the limit that  $\sin^2\theta_W = \frac{1}{4}$ , the following relation holds:

$$\frac{\sigma(\tilde{\tau}_L\tilde{\tau}_L)}{\sigma(\tilde{\tau}_R\tilde{\tau}_R)} = \left(1 + \frac{1}{9(1 - M_Z^2/s)^2}\right), \quad (2.2)$$

and there is little variation in the total rate from left-right mixing. To get the desired cross section, the tau slepton must be fairly light, but it also must have avoided detection at the  $Z$  pole and at other intermediate collider energies. From Fig. 1, it can be seen that a right-handed stau with a mass of about 80 GeV yields the correct cross section, assuming

that the efficiency is about 0.3. Mixing cannot make the cross section arbitrarily small, so a light tau slepton is already excluded.

As mentioned previously, a large fraction of visible energy is the main characteristic of the signal. An upper bound on the visible energy in each event is roughly the sum of the tau energies. In the rest (\*) frame of the tau slepton, the tau energy is  $E_\tau^* = (M_\tau^2 - M_\psi^2)/(2M_\tau)$ . The boost to the lab frame introduces a factor  $\gamma = E_{beam}/M_\tau$ , and the fraction of visible energy is:

$$x_{vis} \equiv \frac{E_{vis}}{\sqrt{s}} \simeq \frac{2E_\tau}{\sqrt{s}} = \frac{1}{2} \left( 1 - \frac{M_\psi^2}{M_\tau^2} \right). \quad (2.3)$$

This estimate ignores the direction of the boost and the energy lost to neutrinos in  $\tau$  decays, but is useful in distinguishing models. The value of 1/2 is obtained for a light gravitino LSP, which yields a large fraction of visible energy. However, we would have arrived at the same estimate for  $W$  pair production, which is the dominant background, so one should be careful about drawing conclusions about the size of a signal before considering the cuts necessary to reduce the backgrounds. For the case of a neutralino LSP, a fraction .3(.4) requires  $M_{\tilde{N}_1}/M_\tau = .64(.45)$ . This illustrates the necessary mass relations to explain the kinematics of the data.

For  $\Delta M = M_\tau - M_{\tilde{\psi}} > 30$  GeV, the efficiency after the cuts listed in Eq. 2.1 is roughly constant at 0.3 (see Table 3 of Ref. [2]. The efficiencies listed there are in accord with our own simulations). Therefore, a NLSP  $\tilde{\tau}_1 = \tilde{\tau}_R$  with  $M_\tau \sim 80$  GeV and a large mass splitting between the tau slepton and the LSP can explain the tau excess. For a neutralino LSP, this predicts  $36 < M_{\tilde{N}_1} < 51$  GeV for  $.3 < x_{vis} < .4$ . There is no rigorous experimental lower bound on  $M_{\tilde{N}_1}$  if the  $\tilde{N}_1$  wave function contains no Higgsino components. Since the kinematics suggest  $M_{\tilde{N}_1} < M_Z/2$ , and a light Wino- or Higgsino-like LSP requires a light chargino, a neutralino LSP should be Bino-like.

If  $\tilde{\tau}_1 = \tilde{\tau}_L$ , in which case the stau is no longer the NLSP, a light  $\tilde{\nu}_\tau$  is also required by the sum rule  $M_{\tilde{\tau}_L}^2 - M_{\tilde{\nu}_\tau}^2 = -\cos 2\beta M_W^2$ . Once  $\tan \beta$  is larger than a few, it is a good approximation to take the squared mass splitting to be  $M_W^2$ . The lower bound on the sneutrino mass is  $M_Z/2$ , leading to the bounds  $M_\tau \geq 91$  GeV. From Fig. 1, one can estimate that  $\tilde{\tau}_1 = \tilde{\tau}_L$  can be marginally consistent with the data. If one does not assume large  $\tan \beta$ , then  $\tan \beta > 2.31$  allows for  $M_{\tilde{\nu}_\tau} > M_Z/2$  and  $M_{\tilde{\tau}_L} = 80$  GeV.

Apropos to a  $\tilde{\tau}_L$  solution, if the gravitino is the LSP and  $M_{\tilde{G}}$  is heavier than about a meV, the decay  $\tilde{\tau}_L \rightarrow \tilde{\nu}_\tau W^*$  will occur before  $\tilde{\tau}_L \rightarrow \tau \tilde{G}$ , because of the small gravitino coupling to matter. This is not compatible with the data, because of the many  $W^*$  decay modes. Therefore, a gravitino LSP and a light  $\tilde{\tau}_L$  can be rejected. The possibility that  $\tilde{\nu}_\tau$  is the LSP and  $\tilde{N}_1$  is heavy can also be rejected, since the decays  $\tilde{\tau}_L \rightarrow W^* \tilde{\nu}_\tau$  would also occur. On the other hand, the mass hierarchies  $M_{\tilde{\tau}_L} > M_{\tilde{N}_1} > M_{\tilde{\nu}_\tau}$  and  $M_{\tilde{\tau}_L} > M_{\tilde{\nu}_\tau} > M_{\tilde{N}_1}$  are

viable. For the former case,  $M_{\tilde{N}_1}$  must be close to  $M_{\tilde{\nu}_\tau}$  to satisfy the kinematic requirement  $M_{\tilde{N}_1}/M_{\tilde{\tau}} < .45 - .64$ , while the latter case allows for a substantially lighter  $\tilde{N}_1$ . The existence of  $\tilde{\nu}_\tau$  with  $M_{\tilde{\nu}_\tau} > M_Z/2$  is not very relevant, as long as  $\tilde{\tau}_L \rightarrow \tau\tilde{N}_1$  is the dominant stau decay, since  $\tilde{N}_1 \rightarrow \nu\tilde{\nu}_\tau$  and  $\tilde{\nu}_\tau \rightarrow \nu\tilde{N}_1$  are both invisible decays, and direct  $\tilde{N}_1\tilde{N}_1$  LSP and  $\tilde{\nu}_\tau\tilde{\nu}_\tau^*$  LSP production are difficult to observe.

An admixture of  $\tilde{\tau}_L$  and  $\tilde{\tau}_R$  pair production is possible, and this would lead to mixed kinematics in the data. Kinematic correlations between the tau pair decay products can provide more information on the quantum numbers of the tau slepton. The tau lepton carries  $L$  or  $R$  polarization (in the rest frame of the stau) depending on whether the parent is  $\tilde{\tau}_L$  or  $\tilde{\tau}_R$ . Pair production of  $\tilde{\tau}_R$  then yields a correlation in the kinematics of the decay products of the tau leptons. As an example, if the decays  $\tau_R^- \rightarrow \pi^- \nu_\tau$  and  $\tau_R^+ \rightarrow \pi^+ \bar{\nu}_\tau$  occur, the  $\pi^-$  will tend to be hard while the  $\pi^+$  is soft, *i.e.* the correlation is  $RR \rightarrow \pi_h^- \pi_s^+$  or  $LL \rightarrow \pi_s^- \pi_h^+$  where  $RR$  and  $LL$  denote the stau wave function and a subscript  $s$  or  $h$  denotes soft or hard kinematics. These considerations are relevant even if the tau sleptons are produced through on-shell decays of neutralinos or charginos. This polarization effect is included in our particle-level simulations.

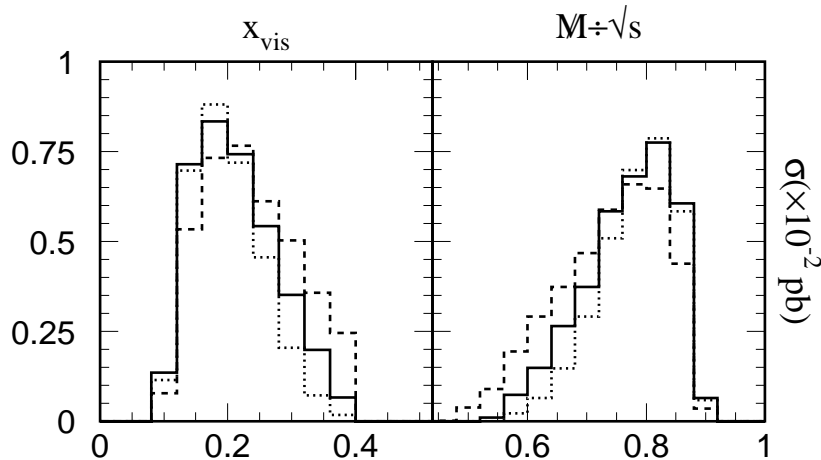


FIG. 2. Kinematic distributions from tau slepton pair production assuming different LSP's and from  $\tilde{N}_1\tilde{N}_3$  production with a  $\tilde{N}_1$  LSP. The dominant  $WW$  background is not included.

To summarize, a tau excess can be explained by tau slepton pair production for a narrow range of tau slepton masses. The cross section (using an efficiency of .3) is compatible with a  $\tilde{\tau}_R$  with mass around 80 GeV. The stau may be left-handed, but large  $\tan\beta$  requires  $M_{\tilde{\tau}_L} > 90$  GeV. The kinematics of the decays suggest  $M_{\tilde{\psi}}/M_{\tilde{\tau}} < .45 - .64$ , so that that  $\tilde{\psi} = \tilde{G}$  or  $\tilde{B}$  is possible. The two LSP cases are kinematically distinguishable, or, more precisely, the mass of the LSP can be inferred from kinematic distributions. This is illustrated in

Fig. 2, which shows the  $E_{vis}$  and  $M$  distributions divided by  $\sqrt{s} = 200$  GeV for  $M_{\tilde{\tau}_R} = 80$  GeV and a neutralino LSP with  $M_{\tilde{N}_1} = 36$  GeV (solid lines) and a gravitino LSP (long-dashed lines). The distributions from  $\tilde{N}_1\tilde{N}_3$  production are also shown (short-dashed lines) for  $M_{\tilde{N}_1} + M_{\tilde{N}_3} = 185$  GeV and  $M_{\tilde{\tau}} = 90$  GeV. The dominant  $WW$  background is not included. A measurement of the cross section at several energies, as well as analysis of kinematic distributions such as these, would allow the various scenarios to be separated.

## B. Neutralino Pair Production

The production and decay chain  $e^+e^- \rightarrow \tilde{N}_1\tilde{N}_j$ ,  $\tilde{N}_j \rightarrow \tilde{\tau}\tau$ ,  $\tilde{\tau} \rightarrow \tau\tilde{\psi}$ , where  $\tilde{\psi}$  is the LSP and  $j = 2$  and/or 3, can also yield a tau pair and missing energy. The case of  $\tilde{\psi} = \tilde{N}_1$  is considered here with a brief comment on a gravitino LSP. The relevance of 3-body decays of the neutralino is also addressed. The  $\tilde{N}_1\tilde{N}_j$  process can be kinematically accessible before chargino and possibly tau slepton pair production. The kinematic requirements set by the data are that  $M_{\tilde{N}_j} - M_{\tilde{N}_1} \sim 80$  GeV, while the production cross section requires  $183 < M_{\tilde{N}_1} + M_{\tilde{N}_j} < 189$  GeV, so that  $M_{\tilde{N}_j} \sim 135$ ,  $M_{\tilde{N}_1} \sim 55$  GeV is marginally plausible. Of course, it is necessary that  $M_{\tilde{N}_j} - M_{\tilde{N}_1} < M_Z$  to prevent  $\tilde{N}_j \rightarrow \tilde{N}_1 Z$  as the dominant decay.

The production of neutralino pairs proceeds through the  $Z$  in the  $s$ -channel or through  $t$ -channel exchanges of selectrons. In the notation of Haber and Kane [6], the  $Z\tilde{N}_1\tilde{N}_j$  coupling is  $O_{1j}''^L = -\frac{1}{2}N_{13}N_{j3}^* + \frac{1}{2}N_{14}N_{j4}^*$ . For  $\tilde{N}_1\tilde{N}_j$  production to be relevant, both neutralinos must have some Higgsino component. This requirement means that the  $Z^*$  contribution to the decay can be significant if 2-body decays are not allowed. Because the excess appears in tau lepton final states, we assume the selectron is not too light.

Since the  $\tilde{N}_1$  wave function should contain some Higgsino component, it is necessary to consider the LSP contribution to the invisible width of the  $Z$ . We require that  $\Gamma(Z \rightarrow \tilde{N}_1\tilde{N}_1)$  is less than 3.0 MeV [7] when  $M_{\tilde{N}_1} < M_Z/2$ , where the  $\tilde{N}_1\tilde{N}_1$  contribution is:

$$\Gamma(Z \rightarrow \tilde{N}_1\tilde{N}_1) = \frac{\alpha M_Z \beta}{6 \cos^2 \theta_W \sin^2 \theta_W} \left[ |O_{11}''^L|^2 (1 - r^2) - 3r^2 \text{Re}((O_{11}''^L)^2) \right]$$

$$r = \frac{M_{\tilde{N}_1}}{M_Z} \quad \beta = \sqrt{1 - 4r^2}, \quad (2.4)$$

with  $O_{11}''^L = -\frac{1}{2}N_{13}N_{13}^* + \frac{1}{2}N_{14}N_{14}^*$ .

Two-body decays of  $\tilde{N}_j$  can satisfy the kinematic requirements if there is sufficient mass splitting  $M_{\tilde{N}_j} - M_{\tilde{\tau}}$  so that the tau produced in the cascade  $\tilde{N}_j \rightarrow \tilde{\tau}\tau$  is not too soft. As before, it is useful to have a simple estimate of the kinematics  $x_{vis}$ . Again, the visible energy is approximately the sum of the tau energies. Since the tau leptons result from the cascade decays of heavy objects,  $\tilde{N}_j \rightarrow \tau\tilde{\tau}$ ,  $\tilde{\tau} \rightarrow \tau\tilde{N}_1$ , the tau energies can be approximated by their values in the rest frame of their individual parents. This assumes that the kinematic boost is small. The fraction of visible energy can then be described approximately by:

$$x_{vis} \simeq \frac{1}{\sqrt{s}} \left( \frac{M_{\tilde{N}_2}^2 - M_{\tilde{\tau}}^2}{2M_{\tilde{N}_2}} + \frac{M_{\tilde{\tau}}^2 - M_{\tilde{N}_1}^2}{2M_{\tilde{\tau}}} \right). \quad (2.5)$$

The example noted above,  $M_{\tilde{N}_j} \sim 135$  GeV,  $M_{\tilde{\tau}} \sim 95 - 100$  GeV,  $M_{\tilde{N}_1} \sim 55$  GeV, can satisfy the nominal kinematic requirements, with  $x_{vis} \simeq 0.3$ . Because of the  $p$ -wave suppression of the production cross section,  $\tilde{\tau}\tilde{\tau}$  production would be negligible in this situation.

The example cross sections shown in Figure 1 for neutralino pair production are within range of the observed tau excess, while large values of  $x_{vis}$  can be obtained for sufficiently large mass splittings. A scan over a range of  $M_1, M_2, \mu$  and  $\tan\beta$  revealed solutions of the form:

$$183 < M_{\tilde{N}_1} + M_{\tilde{N}_2} \leq 190 \text{ GeV}, \quad x_{vis} \geq .3, \quad M_{\tilde{C}_1} \geq 100 \text{ GeV}, \quad \Gamma(Z \rightarrow \tilde{N}_1\tilde{N}_1) < 3 \text{ MeV}, \\ \sigma(\sqrt{s} = 192 \text{ GeV}) \times \epsilon \geq .03 \text{ pb}, \quad \sigma(\sqrt{s} = 200 \text{ GeV}) \times \epsilon \geq .03 - .06 \text{ pb}, \quad (2.6)$$

where  $\sigma$  is the total sparticle production cross section and  $\epsilon$  is the detection efficiency using the cuts described in Eq. 2.1. For each case,  $M_{\tilde{\tau}}$  was chosen to maximize  $x_{vis}$ . The efficiencies  $\epsilon$  from particle level simulations are approximately 0.3, similar to those obtained for tau slepton pair production. To decrease the size of the production cross section  $\sigma(\tilde{N}_1\tilde{N}_j)$  to a plausible level, the selectron mass parameters were both fixed at 300 GeV. The requirement of a heavy chargino not only prevents chargino pair production, but also suppresses the decay  $\tilde{N}_j \rightarrow \tilde{C}_1 f \bar{f}'$ .

The observed cross section  $\sigma \times \epsilon$  is allowed to be as large as .06 pb, since there is some flexibility in setting the overall rate. A heavier selectron mass will significantly reduce the  $\tilde{N}_1\tilde{N}_j$  cross section. Tau slepton pair production also contributes to the total event rate, and left-right mixing can reduce the  $\tilde{\tau}\tilde{\tau}$  contribution, or the tau slepton mass can be larger than the value with maximizes the estimate  $x_{vis}$ , thereby reducing the cross section. If  $\tilde{\tau}_L$  is light, instead of  $\tilde{\tau}_R$ , then the decay  $\tilde{N}_j \rightarrow \tilde{\nu}_\tau \bar{\nu}_\tau \rightarrow \nu_\tau \bar{\nu}_\tau \tilde{N}_1$  will reduce the visible cross section.

Some solutions had  $\tilde{N}_1\tilde{N}_3$  production as the dominant production mechanism, while others had only  $\tilde{N}_1\tilde{N}_2$ . For  $\tilde{N}_1\tilde{N}_3$ , the solutions clustered into the regions  $110 < |\mu| < 140$  GeV,  $M_2 > 200$  GeV,  $50 < M_1 < 90$  GeV (the exact upper and lower bounds depend on the sign of  $\mu$ ), with no real constraint on  $\tan\beta$ . For  $\tilde{N}_1\tilde{N}_2$  production, the regions are  $100 < |\mu| < 135$  GeV,  $M_2 > 250$  GeV,  $70 < M_1 < 135$  GeV. Surprisingly, the  $\tilde{N}_1$  LSP in all solutions has a large Bino composition, with  $|N_{11}^2|$  in the range .3 - .8 for  $\tilde{N}_1\tilde{N}_2$  production, and .6 - .9 for  $\tilde{N}_1\tilde{N}_3$  production. The requirement that  $M_{\tilde{C}_1} > 100$  GeV strongly affects the solutions. Figure 3 shows the relation between the chargino mass and the observed cross section at  $\sqrt{s} = 200$  GeV for the dominant  $\tilde{N}_1\tilde{N}_2$  solutions (o) and  $\tilde{N}_1\tilde{N}_3$  ones (x). The chargino is never heavier than 125 GeV, and some solutions predict that the threshold for pair production is close to the current LEP2 energy.



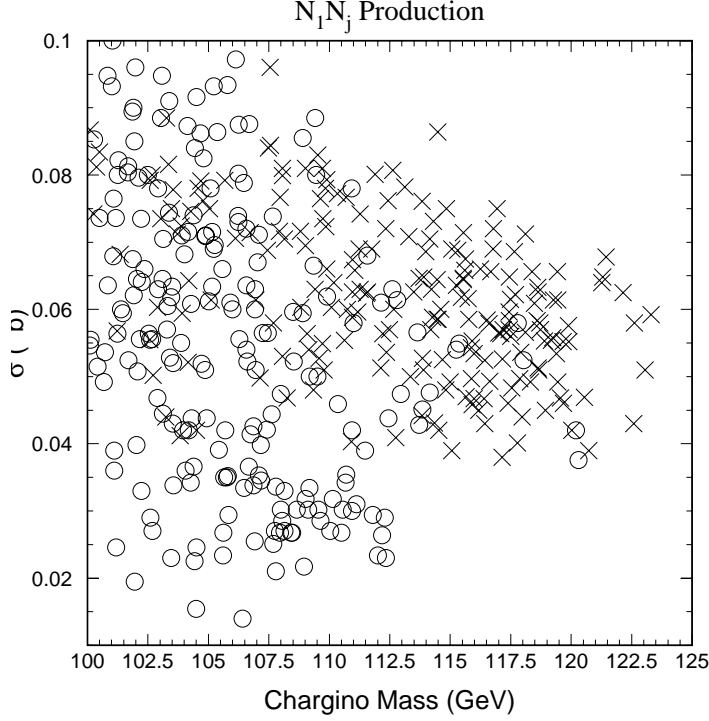


FIG. 3. Relation between production cross section times efficiency and the chargino mass at  $\sqrt{s} = 200$  GeV for  $\tilde{N}_1\tilde{N}_j$  production.

To summarize,  $\tilde{N}_1\tilde{N}_j$  production can produce the correct tau excess by providing an indirect source of tau sleptons. In essence, the  $\tilde{N}_1\tilde{N}_j$  process extends the possible range of tau slepton masses beyond that derived solely from direct stau production. The neutralino LSP should also be Bino-like, but mainly for kinematic reasons.

#### Comment on 3-body Decays:

The decay  $\tilde{N}_j \rightarrow \tau^+\tau^-\tilde{N}_1$  can have a large branching fraction in this case only if the tau slepton contribution can overcome the  $Z^*$  one. This requires a light tau slepton and large  $\tan\beta$ . In the pure Higgsino limit, the equality of the stau and  $Z^*$  couplings requires  $g/(2\cos\theta_W) \sim gm_\tau \tan\beta/(2M_W\sqrt{2})$  or  $\tan\beta = 73$ , where we have taken  $N_{13} = -N_{14} = N_{23} = N_{24} = 1/\sqrt{2}$ . Color factors and additional couplings increase this value somewhat, which is already beyond perturbative limits. Therefore, the mechanism of  $\tilde{N}_1\tilde{N}_j$  production, followed by the 3-body decay of  $\tilde{N}_j \rightarrow \tau^+\tau^-\tilde{N}_1$ , is not very promising in explaining the tau excess.

#### Comment on GMSB:

In GMSB,  $\tilde{N}_1\tilde{N}_1$  production is a possible source of tau leptons if the tau slepton is the NLSP. However, there are several difficulties: (1) four tau leptons will be produced in the final state – two may be soft, but some of these should still be visible; (2) one half of the time the two hardest taus will have the same charge; (3) small  $\mu$  is needed, which is difficult to achieve in the minimal model. Other production modes, such as  $\tilde{N}_i\tilde{N}_j$  or  $\tilde{C}_1\tilde{C}_1$ , will produce

final states with too much structure from cascade decays.

### C. Chargino Pair Production

Chargino pair production does not appear to be a viable explanation of a tau excess. However, it is possible that a slight increase in collider energy will cross the kinematic threshold for chargino pair production, so a brief discussion is in order.

Chargino pair production at LEP proceeds mainly through the coupling of the chargino pair to an off-shell photon or a  $Z^0$  boson or  $t$ -channel electron sneutrino exchange. The  $Z\tilde{C}_1\tilde{C}_1$  coupling depends on  $O'_{11}{}^L = \sin^2\theta_W - |V_{11}|^2 - \frac{1}{2}|V_{12}|^2$  and  $O'_{11}{}^R = O'_{11}{}^L(V \rightarrow U)$ , *i.e.* the coupling is significant whether the chargino is Wino-like, Higgsino-like, or of a mixed composition. For this reason, the chargino production cross is large compared to other sparticle processes in almost any model. The total cross section does depend on the electron sneutrino mass, and a light electron sneutrino can significantly reduce the event rate by an order of magnitude from the heavy sneutrino limit. The example cross sections shown in Figure 1, for the case of  $M_{\tilde{\nu}_e} = 100$  GeV, already exhibit a threshold dependence that is too rapid to explain the data. In particular, it is difficult to explain the dip at  $\sqrt{s} = 200$  GeV, though this is challenging for all the scenarios considered. One can consider smaller values for  $M_{\tilde{\nu}_e}$ , but  $M_{\tilde{\nu}_e} < M_{\tilde{C}_1}$  will lead to an electron excess.

It is important to note that chargino pair production can yield the correct kinematics. The decay  $\tilde{C}_1 \rightarrow \tilde{\tau}_R \nu_\tau$  through a Higgsino component of the chargino wave function will produce energetic tau leptons from the  $\tilde{\tau}_R$  decay. The same is true for  $\tilde{\tau}_L$ , except this does not require Higgsino components to the chargino, and there will also be the decay  $\tilde{C}_1 \rightarrow \tilde{\nu}_\tau \tau$ . If  $M_{\tilde{\tau}_L} > M_{\tilde{C}_1}$ , then the latter decay may be the dominant one. The decay  $\tilde{\nu}_\tau \rightarrow \nu \tilde{\psi}$  is assumed to complete the chain, so that these decays will be essentially invisible. Large values of  $x_{vis}$  are obtained for  $\tilde{C}_1 \rightarrow \tilde{\tau} \nu_\tau, \tilde{\tau} \rightarrow \tau \tilde{\psi}$  if  $M_{\tilde{\tau}} \sim M_{\tilde{C}_1} > .45 - .64 M_{\tilde{\psi}}$ . The decay  $\tilde{C}_1 \rightarrow \tilde{\nu}_\tau \tau$  requires  $M_{\tilde{\nu}_\tau} < .45 - .64 M_{\tilde{C}_1}$  to generate large  $x_{vis}$ .

### III. THEORETICAL CONSIDERATIONS

In this section, we analyze the values of the soft SUSY-breaking parameters that are consistent with the kinematics and event rate of a tau excess. One concern is how to arrange for an excess in only tau leptons. The phenomenological analysis of the previous section requires that a tau slepton is lighter than the selectron. This is not unreasonable, since the connection between the selectron and stau masses depends on theoretical prejudice. At the high mass scale where the soft SUSY-breaking parameters of the MSSM are initially induced, the mass parameters associated with the selectron and stau may only be loosely related. For example, if the sleptons have a common mass parameter at the Planck scale,

the evolution of these parameters to the GUT scale, where extra GUT fields are decoupled, can lead to non-universality. There are potentially several different mass scales associated with different physics (the GUT scale physics, compactification scale, *etc.*) which may have different particle content, thresholds, *etc.* Alternatively, the mass parameters will be highly correlated in specific models such as mSUGRA or minimal GMSB. Here, the consequences of some high mass scale assumptions are examined.

Assume that there is a common origin to slepton masses from universal boundary conditions at some high mass scale. If there is essentially no evolution of the mass parameters so that the selectron and stau mass parameters are the same at the weak scale, then the presence of off-diagonal terms  $m_\tau \tilde{A}_\tau \equiv m_\tau (A_\tau - \mu \tan \beta)$  in the stau mass matrix will decrease the lightest tau slepton mass. This is the mechanism resulting in a lighter tau slepton as NLSP in GMSB. The relations between the lightest tau slepton mass, the mixing angle  $\theta_\tau$ , and the left- and right-handed selectron masses are:

$$M_{\tilde{e}_R}^2 - M_{\tilde{\tau}_1}^2 = \frac{m_\tau |\tilde{A}_\tau|}{\tan \theta_\tau} \quad M_{\tilde{e}_L}^2 - M_{\tilde{\tau}_1}^2 = m_\tau |\tilde{A}_\tau| \tan \theta_\tau \quad \tan 2\theta_\tau = \frac{2m_\tau \tilde{A}_\tau}{M_{\tilde{e}_R}^2 - M_{\tilde{e}_L}^2}, \quad (3.1)$$

using the convention that  $\cos \theta_\tau \rightarrow 0$  corresponds to  $\tilde{\tau}_1 \rightarrow \tilde{\tau}_R$ . For  $M_{\tilde{\tau}_1} = 80$  GeV,  $|\mu| = 1$  TeV,  $\tan \beta = 50$ ,  $A_\tau = 0$ , and  $\tan \theta_\tau = 10$ , the selectron mass is 123 GeV. In all generality, it is easy to arrange that tau slepton pairs are produced at  $\sqrt{s} = 200$  GeV while selectron (and smuon) pairs are not, but this may not be true within a given theoretical framework. Note that when selectrons are kinematically accessible, they can be produced with a significantly larger cross section than smuon or tau slepton pairs, provided that gaugino-like neutralinos are not too heavy. Since the chargino and neutralino production cross sections at LEP depend upon the selectron and electron sneutrino masses, the data may not be compatible with arbitrarily heavy masses.

In models where there is significant renormalization group evolution of the mass parameters, such as in Supergravity models with boundary conditions at or near the GUT scale, a large  $\tau$  Yukawa coupling can reduce  $M_{\tilde{\tau}_L, \tilde{\tau}_R}$  with respect to  $M_{\tilde{e}_L, \tilde{e}_R}$ . This will cause additional splitting between the lightest tau slepton and selectron mass eigenstates. Roughly, both effects – the presence of off-diagonal terms and the decrease of the diagonal terms – are of equal importance.

Both of these examples of generating a large mass difference between the tau slepton and the selectron require that  $\tan \beta$  is sizeable. This can have other consequences in the sparticle and Higgs sectors, which will be mentioned later. An alternative explanation of only a light tau slepton would be the presence of  $D$ -terms that are specific to third generation sparticles. Finally, in models of “more minimal” Supersymmetry [8], the sfermions associated with the first two generations are naturally heavy, on the order of 1 – 10 TeV. It is straightforward to have a light tau slepton in this approach.

To make the discussion more concrete, consider the tau slepton production scenario in a minimal GMSB model. For large values of  $\tilde{A}_\tau \sim -\mu \tan \beta$ , the lightest tau slepton becomes the NLSP, and is approximately a right-handed tau slepton interaction state significantly lighter than the selectron and smuon [9,10]. The estimate for the kinematics is  $x_{vis} = \frac{1}{2}$ , which is easily consistent with the data. The minimal model predicts that  $M_{\tilde{e}_R} \sim 1.1M_1$  and  $M_{\tilde{e}_L} \sim 1.2M_2$  (ignoring D-terms), leading to the relation  $M_{\tilde{e}_L}/M_{\tilde{e}_R} \sim 2.2$ . Two parameters, for example,  $M_{\tilde{\tau}_1}$  and  $\theta_{\tilde{\tau}}$ , fix the stau and selectron spectrum. Since a fixed cross section is consistent with a range of values for  $M_{\tilde{\tau}_1}$  and  $\theta_{\tilde{\tau}}$ , it is straightforward to check if there are solutions with a heavy selectron. After imposing the restrictions  $M_{\tilde{e}_R} > 100$  GeV and  $|\tilde{A}_\tau| < 50$  TeV, a narrow range of values are compatible with a given cross section; a cross section of (.05, .10, .15) pb requires  $M_{\tilde{\tau}_1} = (88, 81, 74)$  GeV. Within this range, it is always possible for the selectron and smuon to be beyond the kinematic reach of LEP2, with a reasonable value for  $\tilde{A}_\tau$ . The fact that the range of solutions is narrow can be understood from Eq. 2.2, which demonstrates that mixing does not cause a large variation in the cross section. Since  $M_{\tilde{e}_R} \sim 1.1M_1$ , the lightest neutralino may be kinematically accessible at LEP, while the heavier neutralinos and the chargino are definitely not. However,  $\tilde{N}_1$  is expected to be largely  $\tilde{B}$ , so the  $\tilde{N}_1\tilde{N}_1$  production cross section would not be large. It is also possible to increase the neutralino and chargino masses with respect to the slepton ones by adding multiple representations of messengers.

Consider instead tau slepton production with a neutralino LSP. In mSUGRA, the approximate relation  $M_{\tilde{e}_L}^2 = M_{\tilde{e}_R}^2 + .35m_{\frac{1}{2}}^2$  holds, with  $M_1 \sim .4m_{\frac{1}{2}}$ . Assuming  $M_{\tilde{N}_1} = M_1 = 0.4m_{\frac{1}{2}} = .45M_{\tilde{\tau}}$  and repeating the same analysis yields almost identical results as for GMSB. Assuming that  $M_{\tilde{e}_{R,L}} = M_{\tilde{\tau}_{R,L}}$  is conservative, since RGE evolution is likely to reduce the stau mass parameters. One concludes that it is not difficult even within specific models to arrange for a heavier selectron. Of course, strict adherence to the mSUGRA mass relations predicts that the chargino is already kinematically accessible at LEP2, which is not consistent with the data. Values of  $M_2$  or  $|\mu|$  too close to  $M_Z$  will yield too light of a chargino mass. If tau slepton pair production with a neutralino LSP is the correct interpretation of the data, then some mechanism must split the gaugino mass parameters. This may be accomplished with non-universal boundary conditions at the GUT scale, for example.

The neutralino pair production scenario is also outside of the mSUGRA framework, since it requires large  $M_2$  and  $M_1 \sim \frac{1}{2}|\mu|$ . Typical solutions have  $M_2/M_1 > 2.5 - 3.0$ .

There are likely alternative explanations to the tau excess involving SUSY or not, and we have not considered them all. The possibility of R-parity violating decays of  $\tilde{N}_1$  induced by an operator  $LLE$  can be rejected: the simplest argument is that each  $\tilde{N}_1$  decay must involve two charged leptons, leading to four leptons (some of which may be tau leptons) in each  $\tilde{N}_1\tilde{N}_1$  event [11].

## IV. PREDICTIONS FOR FERMILAB

### A. Compatibility with the $\tau\tau\gamma\gamma$ event

The  $e^+e^-\gamma\gamma\cancel{E}_T$  event observed by CDF in Run I [12] garnered much interest as a candidate for SUSY. One compelling explanation was the production and decay of selectron pairs, with each selectron decaying in the cascade  $\tilde{e} \rightarrow e\tilde{N}_2(\rightarrow \gamma\tilde{N}_1)$  [13]. However, upon further analysis, the electron candidate seems to be inconsistent with an electron produced at the production vertex. It may be an electron or a pion from the delayed decay of a tau lepton [14]. While this rules out the selectron explanation, it is consistent with stau pair production.

It would be extremely interesting if the FNAL event and LEP events had a common explanation. It is clear that direct tau slepton pair production **cannot** be the source of the tau excess in this scenario, since photon pairs should also be observed – this also pertains to the GMSB explanation of the FNAL event. Since neutralino pair production is only an indirect source of single tau sleptons, single, hard photons would be observed in this scenario. If there is a tau excess at LEP with a SUSY explanation, then the explanation of the FNAL event must either be a highly improbably fluctuation of a Standard Model process, a gross mismeasurement, or a subtle SUSY effect.

### B. General considerations

There have been several studies on the impact of a light tau slepton on phenomenology at the Tevatron [15–19]. These have focussed mainly on the modifications to the trilepton signature. Based solely on what can be observed at LEP, which may require only a light tau slepton and the LSP, not much more can be predicted for Fermilab without introducing theoretical prejudice.

Direct slepton production has never been considered as a promising avenue for discovering SUSY at hadron colliders. Considering only physics backgrounds from real tau leptons,  $Z/\gamma^*$ ,  $WW$  and  $ZZ$  production will be the dominant sources. Since slepton pair production has a rate of roughly  $10 - 100 \text{ fb}^{-1}$  at the Tevatron, it will be difficult to achieve  $S/B < \frac{1}{10}$ . Establishing a tau slepton signal will clearly be more challenging than establishing a selectron or smuon one, as is the case at LEP.

If neutralino pair production is the source of the tau excess at LEP, then SUSY production rates at the Tevatron will be much larger, because the chargino is light.  $\tilde{N}_1\tilde{N}_j$  production cannot be too large, because the size of the cross section at LEP must be comparable to slepton pair production. Chargino pair production will be a much more copious source of tau lepton pairs, so that  $S/B \sim 1/10$  may be achievable.

Since the LSP should be Bino-like,  $\tilde{N}_2$  and  $\tilde{C}_1$  have similar wave function compositions, so that  $\tilde{N}_2\tilde{C}_1$  is a large cross section, leading to the tri-tau signatures considered in previous studies. If  $\tilde{N}_2$  is Higgsino-like, then  $\tilde{N}_2\tilde{N}_2$  production will be a source of up to four tau leptons, though two are likely to be soft. The two hard ones can have the same sign. It is an interesting experimental question whether the **single-prong** hadronic decays of the tau have sufficiently small background to be part of a like-sign signal.

A significant mass splitting between the selectron and stau masses may require moderate or large values of  $\tan\beta$ . Another consequence of large  $\tan\beta$  would be its impact on Higgs boson phenomenology. Properties of Higgs bosons may be significantly altered [20]. In particular, at large  $\tan\beta$ , a sbottom-bottom-gluino loop can shift the bottom quark Yukawa from its tree level value, possibly leading to enhanced light Higgs boson decays to tau,  $W$  and photon pairs. As is usual in large  $\tan\beta$  models, the associated production of Higgs bosons with bottom quark pairs would be a promising avenue for discovering one or more Higgs bosons. If large  $\tan\beta$  is indeed a necessary component of the explanation, then the bottom squark may also be light, leading to a  $b\bar{b}\cancel{E}_T$  signature [21]. The signature is unlikely to be modified by the presence of a light chargino and tau slepton. Of course, in the neutralino pair scenario, the bottom quark cannot be so light that it influences the neutralino decays.

Furthermore, there may be a light top squark, though this is not required by the results of our phenomenological analysis of the tau excess. If we exclude the possibility of a top squark so light that  $\tilde{t} \rightarrow c\tilde{N}_1$  is relevant, then the decay  $\tilde{t} \rightarrow b\tilde{C}_1$  will occur, with  $\tilde{C}_1 \rightarrow \tilde{\tau}\nu_\tau$ . Stop pair production can then lead to a sample of top-like events with an enrichment of tau leptons. Assuming a top squark mass equal to the top mass, and the approximate relation that top squark production is  $\frac{1}{10}$  of top quark production, then there would be roughly 25 events containing  $e$  or  $\mu$  + one hadronic tau decay in  $100 \text{ pb}^{-1}$  of data. If the detection efficiency is several percent, then this would be compatible with the CDF data [22].

For some time, there has been indirect evidence that the gluino is light [23]. Once we give up on the idea of a universal boundary condition for the gaugino masses, as is required by the results of the phenomenological analysis, there is no compelling reason to believe that the gluino is significantly heavier than the LSP. Pair production of gluino pairs or the associated production of gluinos and charginos are a source of like-sign charginos, which decay into like-sign tau leptons. The branching ratio for a pair  $e$  or  $\mu$  leptons from  $\tau$  pair decay is about 12%, but some of the leptons may be fairly soft. Clearly, the use of hadronic tau decays will improve the experimental sensitivity.

To summarize, a tau excess at LEP may translate directly into a tau excess at Tevatron if a number of sparticles are light. Some likely light candidates are the gluino and the bottom and top squarks. The reasons that each of these are light, however, may have different physics origins that are not directly related to the existence of a light tau slepton.

## V. COSMOLOGICAL CONSEQUENCE OF A LIGHT TAU SLEPTON

One interesting consequence of a stable LSP is a potential solution to all or part of the dark matter problem. A consistent explanation of the tau excess in models with a neutralino LSP led us to consider a right-handed tau slepton and a Bino-like LSP. For such a case, the relic abundance is given by [24]:

$$\Omega h^2 = \frac{M_{\tilde{\ell}_R}^2}{M_0^2 \sqrt{N_F} \frac{1}{3} N_{\tilde{\ell}_R}} r^{-2} \frac{(1+r^2)^4}{1+r^4}, r = \frac{M_{\tilde{N}_1}}{M_{\tilde{\ell}_R}}, \quad (5.1)$$

where  $M_0 \simeq 460$  GeV,  $N_F = 606/8$  for the mass range under consideration, and  $N_{\tilde{\ell}_R}$  counts the effective number of light right-handed sleptons.  $N_{\tilde{\ell}_R} = 3$  for three mass degenerate right-handed sleptons, and  $= \sin^4 \theta_\tau$  when a light stau dominates with mixing angle  $\theta_\tau$ . Based on the kinematic analysis of the data, the range  $.45 < r < .64$  can be compatible with the observed  $x_{vis}$ . Fixing  $M_{\tilde{\tau}_R} = 90$  GeV and  $N_{\tilde{\ell}_R} = 1$  leads to the range  $.10 < \Omega h^2 < .12$ . Larger values can be obtained if the purity of the stau eigenstate is reduced, smaller ones if the selectron and smuon are also light (but heavier than the stau). Effects such as co-annihilation or  $Z/h$  pole can only diminish the relic abundance. In the neutralino pair production scenario, the Bino composition of the LSP  $\equiv |N_{11}|^2$  is approximately  $\frac{1}{2}$ , leading to a relic abundance almost twice as large.

In the approximations made in the kinematic analyses above, the visible energy fraction is consistently  $x_{vis} = 1/2(1 - r^2)$ . For the case of neutralino pair production and decay, this requires that the contribution from the  $\tilde{N}_j$  decay and from the tau slepton decay are similar in magnitude, which is reasonable. Using this relation, it is possible to re-express the equation above in terms of a collider observable. Using the previous example but without fixing  $r$ , one finds:

$$\Omega h^2 \simeq \frac{.1}{1 - 2x_{vis}} \frac{(1 - x_{vis})^4}{1 - 2x_{vis} + 2x_{vis}^2}. \quad (5.2)$$

This relation indicates that  $\Omega h^2 \simeq .1$  is expected unless the mass splitting between the NLSP and LSP is quite large, leading to  $E_{vis}/\sqrt{s} \rightarrow \frac{1}{2}$ .

## VI. DISCUSSION AND CONCLUSIONS

This study has considered the interpretation of a tau excess at LEP within the MSSM. After an analysis of the size of the cross section, the kinematics, and the absence of other signatures, we conclude that the most likely explanation of a tau excess at LEP is neutralino or tau slepton pair production. Here, we summarize the various scenarios considered to generate an excess of only tau leptons with a fairly large fraction of visible energy. Direct

tau slepton pair production may be the dominant source of a tau excess. The cross section for  $M_{\tilde{\tau}} = 80$  GeV is in agreement with the data. Unless  $\tan\beta$  is small, a right-handed tau slepton is preferred. A gravitino LSP can easily accommodate the kinematics, as well as a neutralino LSP with mass less than about  $.45 - .64 M_{\tilde{\tau}}$ . A neutralino LSP should be Bino-like to be consistent with the invisible width of the  $Z$  boson. For the case of a neutralino LSP, many motivated models would predict other light sparticles within reach of LEP searches, but there is no such prediction from our phenomenological analysis.

Alternatively, the associated production of neutralino pairs  $\tilde{N}_1\tilde{N}_2$  and/or  $\tilde{N}_1\tilde{N}_3$ , followed by two-body decays of the heavy neutralinos to a tau and stau, may be the dominant source of a tau excess. The tau slepton should have a mass that is separated enough from both neutralino masses so that the tau leptons are fairly energetic. The allowed values of  $M_{\tilde{\tau}}$  extend beyond those compatible with solely direct stau pair production. Despite the fact that the production process proceeds through Higgsino components of the neutralinos, the neutralino LSP has a large Bino component to its wave function. This is fixed by the large mass splitting needed between the two neutralinos to generate the correct kinematics. The chargino is predicted to be light, though not yet kinematically accessible at LEP, or it would influence the neutralino decays or produce its own excess.

Finally, chargino pair production may be the dominant source of a tau excess, but the cross section turns on rapidly above the kinematic threshold, and is not likely to explain all data. It is straightforward to satisfy the kinematic constraints of the observed excess if a stau or tau sneutrino is lighter than the chargino, so chargino pair production will be readily observable once the kinematic threshold is crossed.

Tau slepton pair production with a gravitino LSP falls within the minimal GMSB framework. The case of a neutralino LSP, in conjunction with tau slepton and/or neutralino pair production, requires a deviation from the usual mSUGRA relations between gaugino masses. Neutralino pair production requires  $M_1 \sim \frac{1}{2}|\mu|$  and  $M_2/M_1 > 2.5$ . In all cases, the theoretical framework should predict that the selectron and smuon are heavier than the stau. Large values of  $\tan\beta$  may be necessary to accomplish this.

At LEP, a marginal increase in energy will not substantially increase the tau slepton or neutralino cross sections, and the expected amount of data cannot establish more than a  $4\sigma$  effect [5]. However, in either case, but particularly in the neutralino pair scenario, a kinematic threshold for a new process may well be nearby. If the threshold for chargino pair production is crossed, the tau signal will be enhanced considerably. In such an interpretation, the neutralino can still be a viable CDM candidate.

The situation at hadron colliders, particularly the Tevatron, depends on how many sparticles besides the tau slepton and LSP are light. The production of neutralinos depends on their wave functions, but charginos will likely be produced copiously. The mSUGRA trilepton signature becomes more specifically a tri-tau excess. Top squark decays to bot-



tom and a chargino can lead to top-like events with an excess of tau leptons. Gluino pair or gluino-chargino production can lead to like-sign tau events, which, in turn, can yield like-sign  $e$ 's or  $\mu$ 's. Knowing some sparticle masses from LEP measurements would greatly enhance detection prospects.

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